Tests of Relativistic Gravity
with a Low Mass Spaceborne Frequency Standard

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Abstract,

A mission concept based on an ultra- stable frequency standard and a multi- beam communications system is discussed. This mission is intended to study Einstein's Equivalence Principle and search for low frequency gravitational waves. The concept is based on a small mission set to conform with the requirements of NASA'S Small Explorer Mission program.

1. Introduction

The most celebrated test of relativity with an atomic frequency standard in space is the experiment referred to as GP 'A, performed by Vessot and collaborators [1] at the Smithsonian Astrophysical observatory. This experiment involved the flight of a hydrogen maser on a Scout rocket in a suborbital trajectory. In spite of the fact that this first " space" clock did not achieve an orbital trajectory, it produced a wealth of information, and placed some stringent limits on various parameters of the relativity theory. In fact the limit set by this experiment on the gravitational redshift prediction of the General Relativity still stands as the most accurate experimental test of this prediction.

1 Despite the success of GP 'A no other experiments involving ultra-stable atomic frequency standards have been performed in space. [2] This should be surprising, given that some of the most exacting tests of physical theories may only be performed with atomic frequency standards in the environment of space. Space is a very suitable environment for atomic clocks which exhibit sensitivity to vibration, temperature fluctuations, and magnetic field variations. Since atomic frequency standards (clocks) produce the most precisely measurable physical parameters, i.e. time and frequency,

flying an ultra-stable standard in space will provide the opportunity to perform some of the most sensitive tests of physical theories.

In spite of the weight of such arguments, two other important conditions must be met before flying an ultra-stable clock in space can 1x: realized. First the characteristic mass and power requirements of the clock should be brought in line with the constraints placed on other space science instruments. Typical mass of space fields and particles instruments are in the vicinity of 1 0 to 1 5 kg, while a space version of ultra-stable hydrogen maser clocks could have a mass ranging from 55 to 75 kg. [3] The mass for space science instruments is a particularly important criterion since the current trend in space missions is towards those that are very small, and more affordable. Second, the case for the significance of the scientific payoff of the mission should be strong enough to compete with other outstanding proposals in space science investigations.

In this paper we will give a brief description of a space flight mission based on an ultra-stable frequency standard and a stable, multi beam communication system for space tests of Relativity. [5] The concept of this " clock mission" is motivated in part by the new space mission paradigm of NASA, encouraging small, low cost spaceflights under the Small Explorer missions (SMEX) program. The si141'X program supports missions which cost no more than 30 million dollars and take no more than three to five years from inception to launch. This should be contrasted with large mission concepts such as Voyager and Cassini which would take as long as fifteen years from inception to launch, and would cost upwards of one billion dollars.

The concept is also based on the recent developments in the trapped ion frequency standards which have pointed to the potential for an ultra-stable clock with mass of about 5 kg> and power requirement of less than 15 W. [4] The clock described in this paper will enable investigations of Einstein's Relativity theory providing new findings to elucidate the domain of its validity. The organization of the paper includes a description of the science content of the mission, followed by an outline of the instrument consisting of the clock and the communications system.

2. General 1 Description

The proposed clock mission consists of a small spacecraft flying the science instrument, which consists of a trapped ion frequency standard and a multi-beam communication system. The mission will be carried out in two phases. In the first phase, the spacecraft will be orbiting Earth and carrying out investigations of Einstein's Equivalence Principle (EEP). This phase will have a duration of sixty days. In the second phase the spacecraft will be inserted in a deep space trajectory to carry out a search for low frequency gravitational waves (GW). This phase will have a duration of 34 months, for a total mission life of three years. While it is anticipated that several other related scientific experiments could be performed with this mission, for the purpose of this paper the science investigation will be limited to EEP and GW.

The scientific investigations with the " clock mission" will be based on a performance corresponding to frequency stability of 1×10^{-15} ,

3. Tests of the Equivalence Principle

Einsteins Equivalence Principle is at the foundation of the geometric view of general relativity, and all other metric theories of gravity. Naturally, then, EEP has been tested in a number of experiments where deviations from predictions of general relativity have been sought. The experimental tests of the equivalence principle have addressed the three aspects of EEP, the local Lorentz invariance, local position invariance, and the weak equivalence principle. [(i) The first type of experiments test the isotropy of nuclear energy levels, or the isotropy of the speed of light in an examination of the degree of violation of Lorentz invariance (1,1 J) from electromagnetism. In the second class of tests, gravitational redshift experiments test the degree of deviation of the redshift from the prescription of metric theories. Finally in the third class of experiments the deviation of the inertial mass from the gravitational mass is examined via the Eötvös type experiments.

These previous tests of EEP have thus far upheld all predications of metric theories of gravity; yet there is renewed interest in seeking a limit whereby the geometric view of gravitation fails. The interest in more exacting tests of EEP stems from recent attempts to formulate a theory of quantum gravity, and a theory for the unification of the gravitational force with other fundamental forces of nature, which predict a failure of the metric view of gravity under certain limits.

The proposed mission is intended to address the test of EEP in a comprehensive manner. Firstly, the orbital phase of the mission will include measurements of the redshift to improve the present limits by a factor of' 20. Secondly, the mercury ion frequency standard will 1x: used to compare frequencies derived from both the mercury isotopes 199 and 201 to directly test local Lorentz invariance in orbit. The proposed test will examine, for the first time, the degree of spatial anisotropy produced by the Earth's field. This will be an important experiment in connection with tests of nonmetric theories of medium range, in contrast to the essentially infinite range theories to which previous experiments were sensitive. Nonmetric theories with medium and short range of particularly important to certain string theories. Finally, results of tests of violations of EEP provided with this mission will complement results expected with S'J EP mission, and will test the Schiff's conjecture. [6]

4. Scarell for Low Frequency Gravitational Waves

Gravitational waves are a predication of Einsteins field equations, as well as all other metric theories of gravity. The existence of gravitational waves is generally believed by theorists, and is indirectly observed by the measurement of the variation

in the rotation rate of binary millisecoi id pulsars. Nevertheless a direct observation of gravitational radiation is considered crucial in physics. This is because gravitational waves interact quite weakly with matter, and unlike electromagnetic radiation that is absorbed or scattered by matter, can provide information regarding the interior of stars and other astrophysical sources. Thus gravitational wave astronomy can complement electromagnetic wave astronomy to provide us with a more complete picture of the universe.

Approaches for the detection of gravitational waves include solid bar antennas, laser interferometers, and an antenna consisting of a ground based receiver/transmitter pair combined with a transponder onboard a spacecraft. This latter approach is suitable for detection of low frequency waves with wavelength corresponding to the light distance between the earth station and the spacecraft.[8] The details of the characteristic signature of a wave detected by this antenna system has been described elsewhere and appears as a Doppler shift in the frequency of the radio link between the spacecraft and the earth station reflecting the buffeting of the spacecraft, the buffeting of the earth station, and the reflected earth buffeting by the spacecraft transponder.

For the clock mission this signature will be enhanced by a multi-beam radio link originally described by Vessot.[5] In this manner, a four-way beam radio communication system including up/down links at three frequency bands will enhance the signal allowing a single gravitational wave pulse to produce a ten signature Doppler response. In addition to enhancing the Doppler signature of the gravitational wave, the multi-beam communications link will help reduce the deleterious effects of the atmospheric noise to improve the signal- to-noise ratio of the measurement system.

5. The Frequency Standard

In order to fulfill the scientific goals of the mission within the constraints of mass and power budgets, a modified version of the mercury ion standard has 1 een designed. This instrument is fashioned after the shuttle trap previously described. The specific modifications of the design over the shuttle trap are intended to take advantage of the vacuum of space, and to accommodate the science objectives for the comparison of the frequencies of the two isotopes of mercury at 199 and 201.

Figure 1 is the schematic diagram of the duo clock for the mission. The ion trap is a three segment version of the sector trap previously descril d. [4, 9] The outer segments are for the production of ions, the optical pumping of the lower ground state hyperfine level, and the observation of the clock transition. The middle segment is the interaction zone where the ions are irradiated with the microwaves to induce the clock transition. Each outer segment has its own electron source and mercury isotope source to produce the ions of the desired isotope. The operation of the clock includes cycles, comprising of the creation of 199 isotope ions in the left segment, and their optical pumping in the lower ground state hyperfine level, followed by shuttling of

the ions to the center segment for interaction with **40.5** GHz radiation produced by a local oscillator. While the 199 isotope ions are in the central trap, 201 isotope ions are created, and optically pumped, in the right hand segment. In the next cycle, the 199 isotope ions are shuttled back to the left-Hall() segment for interrogation, while the 201 isotope ions are shuttled into the central segment to interact with 30 GHz radiation produced by a seem id local oscillator.


2,6 cm

— 26 cm

◄— v

E nd View.
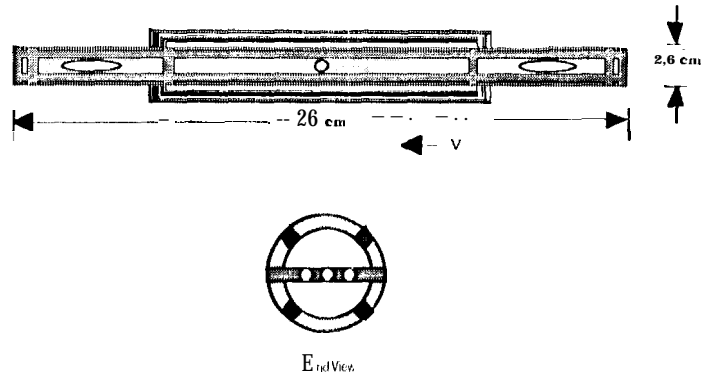
Schematic diagram of the segmented sector trap for the clock mission

The central segment of the trap is isolated with three layers of magnetic shields, which extend beyond the central region to reduce axial fields which might penetrate into the interaction region. An **axial** coil produces the magnetic field on the axis of the central trap for the proper control of the Zeeman sublevels. Appropriate openings in the two outer segments allow the introduction of the uv light, generated by a lamp. Isotope 204 of mercury will be used in the lamp to generate the uv pumping light, since light from this isotope can excite both the ^{199}Hg$^+$ and ^{201}Hg$^+$. Helium buffer gas will enter the trap from one of the end regions. The sector design and the size of the opening windows allow the maintainance of a helium background in 'cssum at about 1 ()" 6 Torr, while the space vacuum provides continuous pumping.

In this manner two standards based on ^{199}Hg$^+$ and ^{201}Hg$^+$ will operate simultane-ously. The frequency derived from each standard will 1)(: used to observe a drift with a signature corresponding to the orbital period of the spacecraft. This observation will last thirty days and data will be integrated and filtered to maximize sensitivity. In the next thirty day period the orientation of the two clocks will be rotated to improve the detection sensitivity of any anisotropy due to Earth's gravity.

After the orbital phase of the experiment is completed, and the spacecraft is in-serted in a deep space trajectory, only one of the clock segments will operate with

mercury isotope 199, and the other segment will remain dormant to serve as a redundant system for the electron source and the lamp.

Optical pumping scheme for the duo-clck
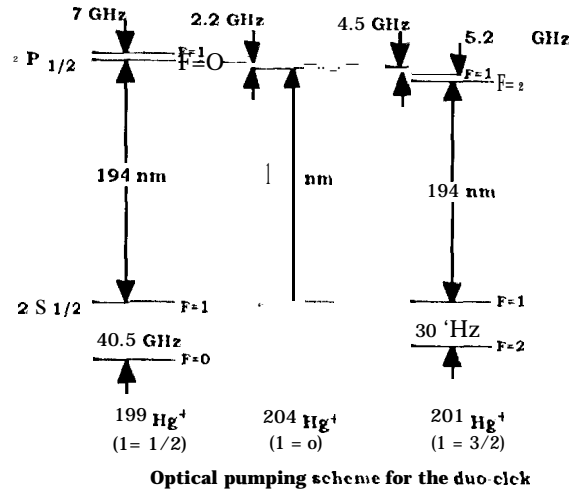
An important part of this relativity instrument is the communications subsystem of the spacecraft. As mentioned before, the multi-beam communications, is crucial to the sensitivity and success of GW observation. The proposed system will not be described here, but will essentially consist of the Cassini transponder and a phased array antenna to reduce mass and power consumption.

Acknowledgements

References

[1] R. F. c. Vessot et. al., *Phys. Rev. Lett.*, **45**, 2081 1980.

[2] Here we are concerned with experiments requiring sensitivities that are only produced by ultra- stable standards. There have been several tests of physical theories using cesium beam clocks in the satellites that comprise the Global Positioning System (GPS). See, for example, D. w. Allan, M. A. Weiss, and N. Ashby, *Science*, **228,69, (198[)**. The stability of these clocks, however, are not sufficiently high to perform the type of tests discussed in the present paper.

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[7] see Prestage *et al. Phys. Rev. Lett.* **54**, 2387 (1985); Lamoreaux *et al. Rev. Lett.* **57**, 3125 (1986) and Chupp *et al. Phys. Rev. Lett.* **63**, 1541 (1989).

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